STRENGTH OF GLASS

Prepared for: SPO 24033
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PROJECTOR DIVISION

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Introduction

The following report is a compilation of a number of interim reports concerning tests performed on plate glass to determine its resistance to temperature and pressure stresses. The first part is concerned with the resistance to temperature only and to a combination of pressure and temperature. The succeeding parts are concerned with pressure tests only.

PART I

1.0 GENERAL

A number of tests were conducted on the mechanical properties of plate glass discs insofar as their resistance to temperature and pressure were concerned.

Two series of tests were run; a temperature test in the absence of pressure and a combined temperature and pressure test. Briefly, these tests were conducted as follows:

1.1 TEMPERATURE TEST

A glass disc was simply mounted at its edges by clamping it between two aluminum plates with "O" ring gaskets. The "O" ring gaskets were coated lightly with silicone grease. The diameter of the supporting edge was 1/2" less than the diameter of the glass disc sample. Torque on the bolts was set at 5 inch-pounds. The bolts were 8-32 machine screws.

The plate supporting the sample was the cover over a well insulated box containing an electric hot plate of 660 watt capacity. The surface of the hot plate was 1½" distant from the glass surface. An 18" household type fan was permitted to blow a stream of air across the "cold" face of the test sample. The surface temperature of the glass was measured at four points with four constantan-copper thermocouples. Precautions were taken that the true surface temperature and not that of the surrounding air layer was measured. The four points were near the edge of the sample on hot and cold sides, and at the center of the sample at hold and cold sides. With the test set up the heat was applied and time and temperatures recorded. The temperature was permitted to increase until rupture occurred. See Table I.

1.2 PRESSURE AND TEMPERATURE TEST

In these tests the glass sample was supported as described above except that the aluminum support plate was the cover of a pressure vessel. Water was used as the pressure medium. All air was removed from the system by suitable venting so that all of the glass surface was in contact with the water. A standard pressure of 10 psi gauge (accuracy ± 1 psi) was used throughout all tests. Bolt torque on the sample support was 5 inch-pounds.

The surface of the glass exposed to the atmosphere was heated in the same fashion as described for the temperature tests. Here, of course, no circulating fan was used. Four thermocouples were used to measure center and edge temperatures. See Table II.

1.3 SUMMARY OF TEMPERATURE TESTS

Seven inch diameter plate glass samples of various thicknesses were tested to destruction. The support diameter was $6\frac{1}{2}$". No record of the glass composition is available but standard soda-lime glass is assumed. All samples had polished edges and a minimum of surface scratches and flaws (i.e. no scratches apparent to eye). After clamping and prior to testing, the samples were tested for strain in a polariscope. No initial strain due to clamping or glass conditioned was detectable in any of the samples tested.

1.4 SUMMARY OF PRESSURE-TEMPERATURE TESTS

After the test setup was completed, a 10 psi pressure was established before the application of heat. This pressure was then maintained throughout the application of gradually increasing heat. Eight inch diameter glass discs with polished edges were used. They were supported on a $7\frac{1}{2}$" diameter. A variety of thicknesses were tested. Glass composition is assumed to be soda-lime. No polariscope strain tests prior to testing were possible.

1.5 CONCLUSION

It would seem that resistance to fracture due to thermal stresses increases with thickness for steady temperature conditions. Although the supports were designed to represent simple supports, there is probably some constraint leading to a support which is quasi-constraining in nature. Polishing edges to reduce sources of local stresses (nicks, scratches) is worthwhile. The average (for design) tensile strength of plate glass at rupture is approximately 6,500 psi as concluded from these tests. No claim is made to represent these figures as true sampling. For this reason, no percent accuracy of data is indicated.

TABLE 1

Thickness (Inch)	Temperature Difference Between Hot and Cold Surfaces (Through Thickness) °F. at Time of Fracture: Near Edge	Center	Max. T	Max. Temp. °F	Elapsed Time to Fracture Min.	Approx. Rate of Temp. Inc. °F/Min. (Start at Room Temp.)	Computed Max. Stress, psi (Note (1))	Remarks
.061	56	52	65	267	14.6	13	6,200	Unpolished edge, fracture started at edge. 10 in.-# bolt torque. Green color.
.068	71	108	108	315	35.5	7	10,300	Polished edge. 4 in. # bolt torque. Green color. Fracture Started at edge.
.133	82	78	102	262	13.2	14	9,750	Unpolished edge, fracture started at edge. 10 in.-# bolt torque. Water white.
.133 (3 scratches)	151	172 NO FRACTURE	236	502	----	7		No fracture. Polished edge.
.133	147	153 NO FRACTURE	170	452	----	5.5	16,000	No fracture. 5 in.-# bolt torque. Green color.
.242	206	----	----	467	----	9	19,700	No fracture. 10 in.-# bolt torque. Water white. Edge temp. 296° F.
.242 (3 scratches)	210	202 NO FRACTURE	220	497	----	7		No fracture. Polished edge
.385	298	---- NO FRACTURE	----	572	----	9	28,400	No fracture. 10 in.-# bolt torque. Water white. Edge temp. max. 419° F.
.510	----	252	----	462	----	12	24,000	No fracture. 10.-# bolt torque. Green color

TABLE I (continued)

Note (1)

Computed from formula: $S = \frac{\alpha E\theta}{2(1-\mu)}$

S = stress in psi
α = $82 \times 10^{-7}/^{\circ}C$ thermal expansion
θ = temp. difference in $^{\circ}C$ (from test data, max.)
E = Young's modulus = 10.5×10^{6} psi
μ = Poisson's ratio = 0.22

Ref: Corning Glass and Roark pg. 322, paragraph 5,
also Morey pg. 345.

Theoretically, a simply supported disc should never rupture due to a steady state, uniform temperature gradient across its thickness. The above formulae is for fixed edges.

TABLE II

Thickness (Inch)	Pressure psi Gauge	Temperature difference Between Hot and Cold Surfaces (Through Thickness) °F, at Time of Fracture. Near Edge	Center	Max. T	Max. Temp. °F.	Elapsed Time to Fracture Min. Sec.	Approx. Rate of Temp. Increase °F/Min.	Computed Max. Stress psi (tensile) Note (2)	Remarks
.070	7	0	0	0	70	0	---	24,300	Pressure applied gradually within 1 min. Green color. Fracture started at internal flaw (bubble).
.135	8	0	0	0	70	0	---	7,450	Gradually applied pressure in 1 min. period. Water white. Bad scratch 1¼" long on low pressure side. Failed at scratch.
.252	10	69	99	99	230	39	4	12,700	Water white.
.386	10	95	NO FRACTURE 160	160	268	--	4	17,430	No fracture. Water white. Max. edge temp. 174° F.
Same .386 Sample	10	--	106	---	286	42.5	5	11,230	Reversed sides. Fracture started at edge; suspect edge touched support. Max. edge temp. 161°F.
.501 (both sides tested)	10	142	NO FRACTURE 183	187	380	---	3.4	18,480	Both sides tested (by reversing) making two runs. More severe run tabulation here. No fracture. Max. edge temp. 215°F (1/8" from cold face).

TABLE II (continued)

Note (2)

Computed from formula for simple support, mechanical loading (of Roark, pg. 188 paragraph 1)

$$\text{Max. } s = \pm \frac{3W}{8\pi M t^2} (3M + 1)$$

(at center)

s = stress, tensile (on surface) away from load - i.e. hot surface) in psi
$W = w\pi r^2$
w - unit load psi
r = radius of support
$M = \frac{1}{\nu}$ - reciprocal of Poisson's ratio = 4.55 for glass
t = thickness in inches

Stresses due to temperature computed as before (Note 1). Tabulated stress is algebraic sum of mechanical and temperature stresses.

PART II

2.0 PRESSURE TESTS vs. THICKNESS

A series of pressure tests were made on various thicknesses of 8" O.D. plate glass discs using the pressure test set up described in Part I. Three thicknesses of glass were used; 1/16", 1/8" and 1/4". Prior to testing the blanks were inspected for strain under a polariscope and found to be free of strain. They were then clamped in the pressure tester under 5 inch-pounds of bolt torque. Care was observed to eliminate all air pockets. Pressure was then gradually applied until the glass broke. In almost all cases, the fracture started at a surface scratch which had been noted and identified prior to the test. All discs had polished edges.

Table III is a plot of glass thickness vs. the stress in psi at time of fracture as computed from the stress formula for discs which is:

$$S_{max} = \frac{3\,W}{8\pi\, mt^2}\,(3m+1)$$

(at center)

where: $W = w\pi r^2$ = total load
m = reciprocal of Poisson's ratio = 4.54
t = thickness in inches

The mean thicknesses tested were .0638" which broke at an average pressure of 4.2 psi; .132" which broke at an average pressure of 11 psi, and .253" which broke at an average pressure of 25.7 psi. The support diameter was 7½" OD. It will be noted that the allowable stress decreases with an increase in thickness of glass. Normally, one would expect the curve to be a straight line having a fixed value of stress for any thickness. A theoretical investigation is shown in Part III to determine the reason for this effect.

PART III

3.0 THEORETICAL ANALOG

The following covers an analogy between the mechanical properties of glass and reinforced concrete. Design data on reinforced concrete is well known. In addition, its properties are similar to those of glass in that concrete has considerable strength in compression but none at all in tension. Glass in turn has considerable strength in compression and some strength in tension.

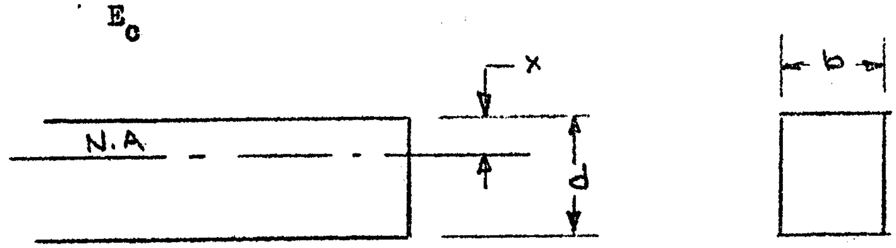
Standard reinforced concrete design requires that the neutral axis of the support member (beam or slab) be determined first. This location is dependent upon the ultimate fibre strength of the concrete in compression and the ultimate fibre strength in tension of the steel reinforcing bars, and in addition the ratio between the modulus elasticity of the steel and the modulus elasticity of the concrete.

PART III (cont)

For purposes of this discussion, the standard nomenclature for concrete design will be used. The basic equations are:

$$k = \frac{f_c}{\frac{f_s}{n} + f_c} \qquad (1)$$

$$n = \frac{E_s}{E_c} \qquad (2)$$



$kd = x$

$$kd = x \qquad (3)$$

For our purposes, we will apply reinforced concrete design data for a beam as if the beam were made of glass. It has been well-established in literature that the tensile strength of glass is the limiting strength. Since the beam is made of glass, the material is homogenous and the value 'n' is therefore unity. Further, it is assumed that the ultimate strength in compression of the glass is a constant and the ultimate strength in tension is a constant, thus the value of 'k' will be constant. Now then the moment in the lower half of a uniformly loaded beam is

$$M = A_s f_s jd \qquad (4)$$

$$\text{where } j = 1 - \frac{k}{3} \qquad (5)$$

f_s = ultimate strength in tension

'A_s' is the area of the glass which is in tension. This in turn will be proportional to a certain skin thickness (value undetermined) multiplied by the width of the beam 'b'. It is this skin thickness which is assumed to vary with the total thickness of the glass. The maximum moment in a simply supported rectangular beam of length 'l' is

$$M_{max} = 1/8\ Wl \qquad (6)$$

where 'W' is the total load, uniformly distributed. If we equate 4 and 6 we have

$$W = K_1\ d \qquad (7)$$

where 'K_1' is a constant dependent upon the shape of the beam and type of load. In the case of a glass beam 'K_1' might vary as 'd' varies or be constant while 'd' is raised to some power. This will be shown later. In the case of a reinforced concrete beam, K_1 will remain constant.

For a rectangular (cross section) steel beam similar equations may be applied. For a uniformly loaded simply supported beam of steel, the maximum moment is given by equation 6. Further, the value of the moment is also given in terms of the beam shape and its ultimate strength by

$$M = \frac{SI}{c} \qquad (8)$$

where $c = \frac{1}{2}d$ & $I = \frac{bd^3}{12}$

Equating equations 6 and 8 we have

$$W = K_2 d^2 \qquad (9)$$

where K_2 is determined by beam configuration and type of load.

It should now be noted that in the case of the concrete design the load varies as the first power of the beam thickness, and in the case of an all steel beam the load varies as the square of the beam thickness.

Almost all beam and plate equations relate the uniformly distributed load to the thickness in the form of the equation

$$W = K_3 d^n \qquad (10)$$

Load tests on glass plate have been reported previously. This data has been used to establish the value of 'K_3' and 'n'. We find that for a disc of $7\frac{1}{2}$" support diameter the value of K_3 is 6930 and the value of 'n' is 1.32. These values have a relatively small spread when applied to any one of the 22 pressure tests made. It is interesting to note now that the equation for a glass structural member lies somewhere between that for concrete and that for steel as evidenced by the exponent for the thickness 'd'.

Three borosilicate plate glass discs were pressure tested and two rectangular borosilicate pieces of plate glass were tested. The values for the ultimate strength as computed from plate data (as given by Roark) fell within the clusters shown in the plot of thickness vs. ruptured strength. Therefore, it may be safely assumed that the ultimate strength of glass due to mechanical loading is 5000 psi. This value is the vertical asymptote of the curve afore mentioned. For thicknesses less than 1/4", this value increases as shown by the same curve.

PART IV

4.0 TOUGHENED GLASS

Consideration was given to the use of toughened glass, and therefore an investigation of the optical properties of toughened (or hardened) glass was made. There was available a 20 mm thick piece of Schott BK-7 glass which had been specially hardened. This type of glass was originally used for submarine periscopes. The glass was considered specially hardened in the sense that the large double refraction normally associated with hardened glass had been reduced. The piece was first examined in a polariscope and showed a strain of approximately 80 milimicrons per centimeter. A 1" aperture collimator was set up and collimated on a reference surface. The disc of hardened glass was then placed near the objective of the collimator and shifted back and forth by hand. Examination of the image in the collimator showed degradation of the point source when viewed with the sample in place. In addition, motion of the sample in the collimated beam caused displacement of the image by approximately 2.5 mils. It was concluded, therefore, that hardened glass would be unsuitable as a window.

Of academic interest is Schott's comment on this glass that its chief value for optical uses was for window material when the light was collimated and 90° incident to its surface. Further, since the glass was hardened glass, polishing should not exceed more than 1 mm removal of the surface of either side.

4.1 ULTIMATE GLASS STRENGTH

As mentioned in Part III, the asymptote to the thickness vs. ultimate strength curve lies approximately at 5000 pounds psi as the ultimate strength of glass for any thickness. This figure should be used with caution, however, because it was based upon test data applied to simply supported plate equations. The actual test did not simulate a true simple support but one which lay approximately midway between a fixed support and a simple support. For purposes of the discussion to follow, this type of test support will be designated as a quasi-simple support. A second plot of thickness vs. ultimate strength was made using fixed plate formulae and the test data. Such a curve was parallel to the original curve but shifted to the left. These two curves then can be considered as designating that the actual test support was an equal combination of simple and fixed supports, a curve of thickness vs. ultimate strength for the quasi-simple support should lie midway between the two aforementioned curves. Actual plots showed that the asymptote for the fixed support lay at 2500 psi. This would then place the asymptote with a quasi-simple support at 3750 psi. This figure (3750) represents the true ultimate strength of the glass.

A theoretical approach may also be used to establish this asymptote as follows: The equation for the maximum strength of a disc in a fixed support is

$$S_f = \frac{3W}{4\pi t^2} \tag{1}$$

For a simple support and using a value of .22 for Poisson's value, the maximum strength is

$$S_s = 1.61 \times \frac{3W}{4\pi t^2} = 1.61S_f \tag{2}$$

If we assume that the strength for a quasi-simple support lies half way between the two, then

$$S' = \frac{S_s + S_f}{2} \tag{3}$$

$$S' = \frac{1.61S_f + S_f}{2} = 1.305\ S_f \tag{4}$$

From our experimental data we then get S_s equal 5000, S_f equal 3000, and S' equal 4050 psi. This is in fairly good agreement with the data derived from the curves.

Thus numerical values of S_s and S_f are fictitious as used here, and their use is restricted to specific plate formulae. However, the value of S' is the true strength of glass. Since we do not have a formula for a quasi-simple support, the true ultimate strength of glass is of not too great a value for this current window problem. For this problem, the value of the ultimate strength should be taken as 5000 psi and used with simple support plate formulae for those cases where the actual mounting is a quasi-simple support.

4.2 SUMMARY

As determined from these tests, the true ultimate mechanical strength of glass lies between 3700 to 4000 psi. This is true regardless of the glass composition since both borosilicate and lime glass were included in these tests.

The attached curve includes data derived from testing borosilicate plate glass discs and rectangles.

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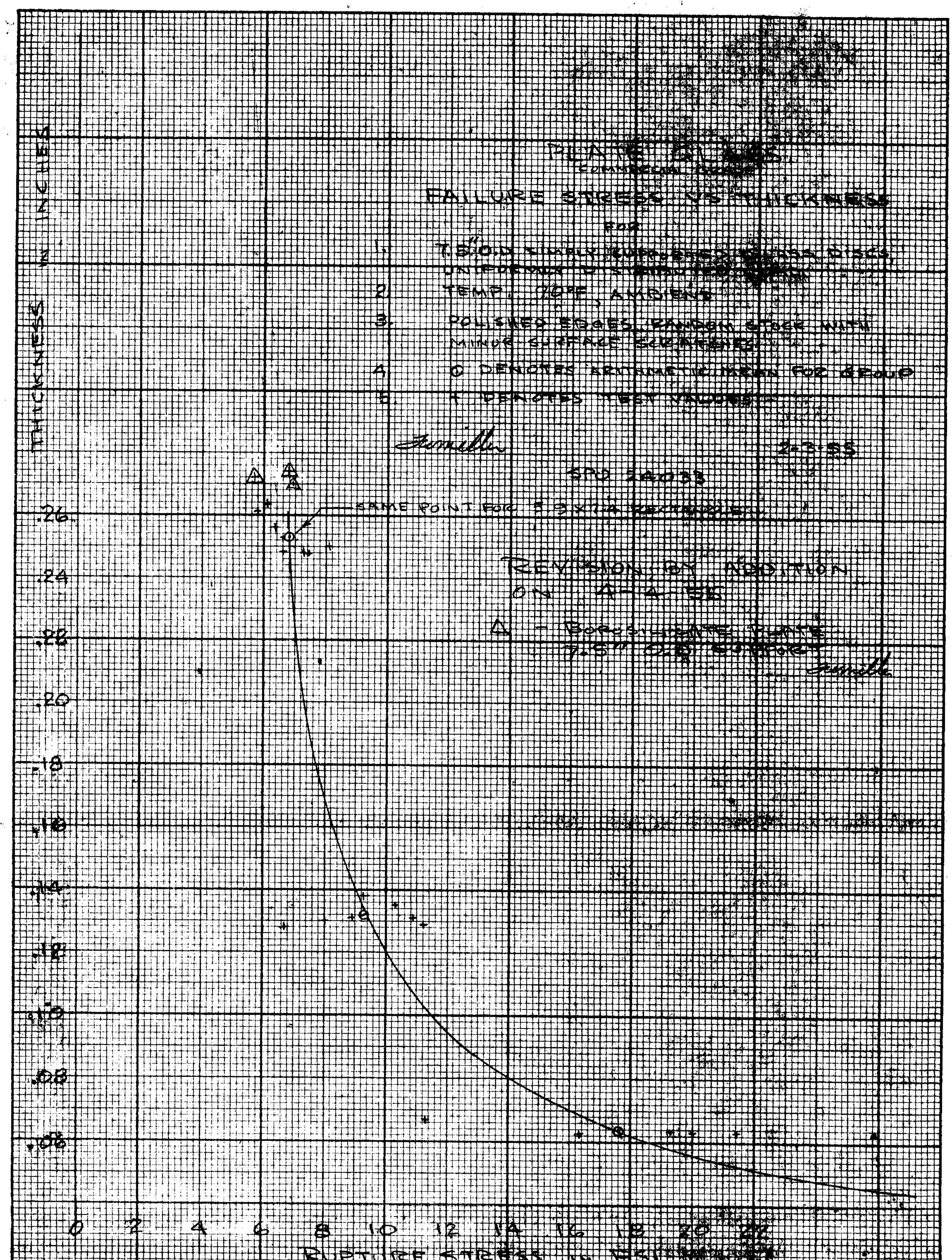
PLATE GLASS
COMMERCIAL GRADE
FAILURE STRESS VS THICKNESS
FOR
1. 7.5" O.D. SIMPLY SUPPORTED GLASS DISCS, UNIFORMLY DISTRIBUTED LOAD
2. TEMP. 70°F, AMBIENT
3. POLISHED EDGES, RANDOM STOCK WITH MINOR SURFACE SCRATCHES
4. ⊙ DENOTES ARITHMETIC MEAN FOR GROUP
5. + DENOTES TEST VALUES
2-3-55
SPD 24033
SAME POINT FOR 5.9X7.4 RECTANGLE
REVISION BY ADDITION ON 4-4-55
△ - BOROSILICATE PLATE 7.5" O.D. SUPPORT
THICKNESS IN INCHES
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
0
2
4
6
8
10
12
14
16
18
20
22
RUPTURE STRESS IN PSI